

Tribology Theory Versus Experiment

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TRIBOLOGY THEORY VERSUS EXPERIMENT

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SUMMARY

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Tribology, the study of friction and wear of materials, has achieved a new interest because of the need for energy conservation. Fundamental understanding of this field is very complex and requires a knowledge of solid-state physics, material science, chemistry, and mechanical engineering. Initiating a research program in tribology requires an understanding of these complexities. The present paper is meant to be didactic in nature and outlines some of the considerations needed for such a program. The approach is to first present a simple model, a field emission tip in contact with a flat surface, in order to elucidate important considerations, such as contact area, mechanical deformations, and interfacial bonding. Then examples, from illustrative experiments are presented. Finally, the current status of physical theories concerning interfacial bonding are presented.

INTRODUCTION

The field of tribology has been only on the fringes of basic science in part because it is dominated by practical engineering and also because of its complexity. In recent years, however, a new awareness has arisen out of the needs for energy conservation. Many scientists who are not familiar with tribology are now initiating research programs, consequently, this paper attempts to give a critical, but not comprehensive, review of certain aspects of tribology. Emphasis is placed on performing basic research with examples directed towards specific phenomena.

A criticism immediately arises when one examines most of the lubrication literature. Usually there are not any error bars on experimental results. This arises because experiments are often not repeated. In addition, in basic science if an interesting phenomenon is discovered, a serious effort will be made by other research groups to reproduce these results. In many situations in tribology, it is not necessarily that the scientists or engineers are not competent or do not know about controls but there are few research groups, and tribology is dominated by making some piece of mechanical equipment work adequately. This equipment domination often involves very specific applications, with ill-defined conditions, which make repetition of the experiment and comparisons from one laboratory to another very difficult. In fact, when round-tables have been held where attempts have been made to control conditions the results, with respect to reproducibility of wear turned out to be poor. The reason may be that the critical parameters for friction and wear have not been determined.

This review will proceed by first considering some simple examples from adhesion and friction experiments in order to demonstrate the complexities involved in defining critical parameters. The effects of geometry, mechanical

properties, and chemistry will be discussed for adhesion and for dry and lubricated-with-additives friction and wear studies. A discussion of the status of adhesion theory, with a special emphasis on the work of Ferrante and Smith (ref. 1), will conclude the paper.

EXPERIMENTAL TRIBOLOGY

One of the discouraging aspects in dealing with tribology problems is that there are only a few research groups devoted to these studies in the world. Because of the complexity of the problems encountered, these groups should ideally consist of an interdisciplinary mix of solid state physicists, material scientists, chemists, and mechanical engineers. It is my experience that, even with this proper mix, communication is difficult and therefore the progress has been slow.

We will now proceed by presenting some of the salient features of mechanical contacts, such as the geometrical properties, mechanical properties, and evidence for adhesion. There are many who argue that adhesion and surface effects are not important in friction and wear. Another title of this presentation could be, Adhesion, friction, and wear: Are there really surface effects? The answer is undoubtedly yes, but how does one design an experiment where they can be detected?

GEOMETRY

Theoreticians deal with ideal flat surfaces where all of the atoms are in periodic arrays, whereas engineers deal with real surfaces which are rough, with a hill and valley structure. Therefore, the problems that engineers face are really much more difficult. In a real contact the true contact area is not equal to the apparent contact area. The surfaces are usually characterized by taking surface profiles. These profiles are often misrepresented in plots of profilometer data (fig. 1) because the horizontal sensitivity is different from the vertical which gives a false impression of surface roughness. A number to remember is that a rough-filed surface has slopes on the order of 10° . There are difficulties involved in examining roughness with the profilometer because when one rolls a stylus such as a phonograph needle over a surface, one cannot accurately represent the shapes of surface asperities or surface defects (fig. 2). One must somehow infer the actual shape from the profilometer traces. In addition, the stylus damages the surface by scratching it. To reiterate, real surfaces are not flat (the way theoreticians would like them to be), even with very carefully prepared surfaces are involved such as would be used for low energy electron diffraction (LEED) studies. In addition, surfaces deform on contact, and this deformation affects the geometry.

Often in simple contact-adhesion experiments, different macroscopic geometries are used (fig. 3). The worst combination is the flat on flat, because in this case you are least able to characterize the true contact area or have any idea of what the true interaction interface is like. Probably the best configuration is the field emission tip on a "flat" surface, since, at least in this case, you are dealing with a very small contact region which is close to a single asperity (ref. 10). In some of the other geometries, such as the crossed cylinders and sphere on flat (refs. 11 and 12), an elastic analysis can be performed which gives some idea of the contact area (the FEM tip on flat is

similar to the sphere on flat). There are many considerations beyond geometry. Mechanical properties are material dependent and interfacial forces are material dependent. Adsorbates affect interfacial forces and mechanical properties.

MECHANICAL PROPERTIES

We will now present the effects of mechanical properties of a solid on adhesion, friction, and wear experiments. Bulk solids can behave both elastically and plastically. With ceramics contacts often behave elastically; some examples of this will be given. For adhesion the interface can be stronger or weaker than the bulk of one or both materials. Consequently, separation can occur either at the interface or in the bulk of one of the materials. In addition, brittle or ductile fracture can occur on unloading an adhesive contact. Thus, loading and unloading of solids to study adhesion is a complicated process involving much more than bonding forces. If we consider a real situation with bearings, lubricants and additives, relative motion and wear debris, we see a very complicated and messy problem.

To simplify and amplify upon the mechanics of a contact, let us think in terms of a single asperity in contact with a flat surface. A simple way to think about a contact with strong adhesion is that it is similar to a tensile test (fig. 4(a)) involving loading the solids and then pulling them apart. An adhesion experiment involves the strength of interfacial forces and deformation of the solids. If the adhesive force is strong enough to form an interface which is stronger than the bulk, failure will occur in the bulk of one of the solids rather than at the interface. In the initial stages of loading, the deformation is elastic and at higher loads, the solids start to deform plastically. The deformation on loading can be monitored by measuring the contact resistance, which would give the true contact area if the resistivity at the interface were known. The difficulty is, of course, that the resistivity for clean metal or adsorbate-covered interfaces are not known. However, simply observing the change in contact resistance reveals a great deal. On contact one finds a sudden decrease in resistance. This drop may occur at close to zero-loading force. A decrease at approximately zero load may be due to adhesive forces. Increasing the load causes the solids to deform. The resistance continues to decrease with load, indicating an increase in contact area. When the process is reversed and the load is removed, the resistance increases. This type of experiment has been performed by a number of laboratories (refs. 3 to 10). The behavior of the contact-resistance loading curve can be very different, depending on the type of solid examined (fig. 4(b)). For an elastic solid with no adhesion, the elastic region of the stress-strain curve is linear as one loads and unloads. With adhesive forces present, it is necessary to apply an additional tensile force at zero load in order to break the adhesive bond. If the solids deform plastically with brittle fracture upon unloading an adhesion, the true contact area changes, and there is a large hysteresis with a sudden fracture occurring at the interface at some negative load. If the solids are ductile upon unloading, such as in the case copper, there is a necking-down of the asperity region, with a gradual increase in contact resistance, and finally, brittle fracture after strain hardening. We can see from the conditions that the analysis of a single asperity contact is quite complex. For more complicated, real contacts, such as with bearings, a phase diagram of properties (refs. 13 and 14) has been defined which describes

regimes of operation (fig. 5). These diagrams include material properties and surface roughness.

We have outlined only some of the complexities which must be dealt with in this multidimensional problem. Other complicating features can be found with only minimum examination. For example, if two hard solids are loaded, the deformation is mainly elastic. When the load is released, the elastic restoring forces are often sufficient to break the bond so that no adhesion is measured. The conclusion from this experiment would be that there was no adhesion at the interface. In ductile solids such as metals, both situations occur, giving both an elastic springback to contribution due to bond-breaking, and an increase in true contact area due to plastic deformation (refs. 11 and 12). Thus the breaking force does not equal the adhesive force (fig. 6). With clean ductile solids, a further complication is introduced by lateral motion. When the applied load reaches a sufficient strength to cause plastic deformation, a flowing of one surface over the other occurs, giving junction growth (fig. 7, refs. 11 and 12). Upon unloading, a large adhesion force is measured. The magnitude of this force is deceiving and reflects the fact that the true contact area has increased due to the junction growth resulting from translational motion. Thus it is important to control vibrations when performing adhesion experiments. With ductile solids one gets junction growth, and with hard solids, the combination of elastic springback and vibrations can break bonds.

Remember, this is not a discussion of bearings and lubricants--but the much simpler case where a single asperity is brought into contact with a flat surface and pulled apart. Time-dependent conditions such as creep must also be considered. Material properties change upon loading, e.g., the occurrence of strain hardening. The stress distributions in a contact are not simple. If adsorbates are present, surface forces and possibly the mechanical properties will be altered.

Let us consider a solid which deforms elastically, such as germanium. If an adhesion experiment is performed as a function of temperature it is found that the hardness of the germanium (ref. 4) decreases substantially with temperature (fig. 8). When examining the adhesive forces, we find that at low temperatures, zero adhesion is measured and as the temperature is increased the adhesive forces increase substantially. If the contact is cooled, zero adhesion is again measured so simply changing the temperature gives an entirely different behavior due to changes in ductility. For a ductile contact, e.g., copper-copper, the adhesive pull-off force is proportional to the joining load because the contact area changes with load (ref. 10). Titanium carbide (ref. 10), which has a fairly high electrical conductivity, is interesting, since adhesive behavior comparable to a metal-metal contact is obtained. To repeat, hard solids give a pull-off force which is much lower than the joining force, and ductile solids give a pull-off force proportional to the load.

An example of adhesive versus materials properties is given from pin-on-disk studies (fig. 9) of clean metal-metal friction and transfer experiments performed by Pepper and Buckley (refs. 15 and 16). These studies were performed in an ultrahigh vacuum system at 10^{-10} Torr, with an Auger spectrometer examining the wear track. The discs were tungsten, tantalum, niobium, or molybdenum, and the riders were iron, nickel, or cobalt. We ask the question, Which way would you expect transfer to occur? The guess, based on adhesive forces, would be that transfer would occur from the iron, nickel, and cobalt to

the tungsten or to any of the other harder metals. But using Auger spectroscopy under very controlled conditions, all transferred to the tungsten. Iron and nickel did not transfer to tantalum, molybdenum, or niobium. Cobalt transferred to everything (tables I and II). If these results seem to be mysterious, it is because adhesion is not the dominant phenomenon. Strain hardening occurs in the iron and nickel and this accounts for the lack of transfer. Cobalt has easy slip systems and therefore transfers easily to the other surface. Consequently, mechanical properties dominate the transfer of one metal to the other even when there are strong adhesive forces present. The same results are also reflected in the surface-roughness and friction coefficient following sliding.

SURFACE EFFECTS

The objective until now has been to emphasize the considerations which are needed for understanding friction and wear experiments. We now wish to address the question of what role, if any, interfacial effects play in tribology. We will first outline some general results and then examine experiments in which interfacial forces play a role.

Some general observations from adhesion experiments can be presented. For metals, the adhesion coefficient, defined as the breaking force divided by the load, is less than unity when vibrations are carefully controlled (ref. 17). If tangential stresses are present however, junction growth occurs and very large adhesion coefficients are obtained such as 10 to 100 (ref. 18). Small values are obtained for hard materials (ref. 17). Bonding is strong for all metal combinations, and transfer is observed (ref. 18). For hard solids, however, there is almost no measurable adhesion, whether vibrations are present or not (ref. 17). For metals in contact with hard solids, there seems to be a strong dependence on the electronic structure (ref. 18). There is a reduction in adhesion between metals when adsorbates are present. For hard solids there are no really good results. For contacts between metals and hard solids few experimental results exist for adhesion, but measurements have been made for static friction. These will be discussed below. Modifying the surface with adsorbates provides the primary evidence for surface effects.

We will now present examples of systems where surface forces dominate. First consider the effects of oxygen adsorption on metallic adhesion done by two methods: (1) a field emission tip on a nickel substrate (ref. 9) and (2) two-crossed iron cylinders (ref. 19). The question is, What is the effect of oxygen on the separation force? Again we are discussing loading and then unloading and measurement of the separation force. For the field emission tip experiment, the metal-metal contact satisfies the relation that the adhesive force is proportional to and of the order of the loading force. At very low loads, the separation force is constant, indicating that the adhesive component of the contact is dominant (fig. 10). If oxygen is adsorbed on the surface, there is an order-of-magnitude reduction in the adhesive and separation forces occurs, indicating that the oxygen reduces the adhesive force at the interface. Partial monolayer coverages of oxygen showed no effect. Also shown in these experiments was the fact that the field emission tip can be used to perform micro-hardness measurements. A large increase in surface hardness occurs when the surface is oxidized. The behavior is very much like an elastic solid. Hartweck and Grabky (ref. 19) used crossed cylinders (fig. 11) to examine the effect of adsorbates on adhesion. They observe an increase in adhesion due to

surface adsorption. This raises an interesting question: How does one detect an increase in adhesion? An increase in bond strength at the interface over the clean materials means that failure should occur in the bulk of the weaker material, consequently, the same value for adhesive separation force for the clean interface should be obtained. Unless of course the interface at the clean contact is weaker than the bulk. In any event, the interpretation is ambiguous.

Wheeler (ref. 20) has used static friction experiments to investigate the effect of adsorbates on metals (fig. 12). These were performed by loading a metal pin against a metal flat and measuring the force needed to initiate sliding. The effects of adsorption of partial monolayers of oxygen and chlorine adsorbed on the surfaces were examined. The experiments were performed in an ultrahigh vacuum system with Auger spectroscopy for characterization. Several metals were used: copper, iron, and steel. In all of these cases there seemed to be no difference in the effects of oxygen or chlorine at partial monolayer coverages if atomic size is included. Adsorption reduced the static friction in all cases. Incidentally, for iron and copper it was not possible to do these experiments with bulk contacts because the mechanical effects dominated the results and gave no reproducibility. Consequently it was necessary to sputter iron and copper on the hard 52100 steel in order to minimize distortion of the substrates. These results can be interpreted quantitatively in terms of a junction-growth model where clean metal is exposed during sliding. For metals, Wheeler's results, and the results of Tabor et al. show that there is a decrease in adhesion and friction with oxidation on metal surfaces.

Pepper (ref. 21) has examined the effects of adsorbates on a metal-insulator contact. The experiments again use pin-on-disk experiments in an ultrahigh vacuum system (fig. 9). The sliding friction results are rather remarkable. What happens is, oxygen adsorbed on the metal increases the dynamic friction coefficient (fig. 13) for a sapphire pin on a metal disc. If the oxygen is removed, the friction coefficient returns to its original value. If chlorine is introduced, a decrease in the dynamic friction coefficient occurs. A gas adsorbed on a metal surface in an ultrahigh vacuum system gives changes in the metal-insulator dynamic-friction force as a function of time. Visual examination of the wear track shows severely roughened surfaces. The dramatic result is that a surface effect occurred in spite of a macroscopic roughening of the surfaces. This effect was further probed in static-friction coefficient experiments.

The experimental apparatus for static friction or interfacial shear measurements consists of a metal ball on an insulating flat (fig. 14). Pepper (ref. 22) observed a difference in static-friction coefficient between the alumina and clean metal depending on the metal. For example, silver gave a low interfacial shear stress as compared to iron (fig. 15). Furthermore, adsorption of partial monolayers on the metal surface also changed the coefficient of static friction. In addition, the direction of the change in static-friction coefficient, relative to the clean metal surface, is adsorbate dependent. Adsorption of oxygen on nickel or copper, for example, increases the static-friction coefficient with single-crystal sapphire; whereas chlorine decreases it (fig. 16). Ethylene also increases the shear strength slightly, and nitrogen decreases it slightly. The same effects occurred on nickel and copper, which are very different. Copper does not readily adsorb the oxygen. The adsorption of partial monolayer coverages indicate that there are surface

effects. Also, there are definite trends in the static coefficient of friction, both as a function of metal and adsorbate. Consequently, these results represent fertile ground for interface theory. As an initial attempt, simply prediction of trends would be sufficient.

Another example of similar results can be found in Pepper's work on diamond (ref. 23). The diamond surface is known to be terminated by hydrogen. Pepper found that hydrogen could be removed either by bombarding the surface with electrons or by heating the diamond surface at sufficiently high temperature in an ultrahigh vacuum system. Following either treatment, an extra feature appears in the electron energy-loss spectrum (fig. 17) that can be identified as extra states lying in the band gap. If the converted surface is exposed to dissociated hydrogen, the extra states disappear from the energy-loss spectrum. The LEED (Low Energy Electron Diffraction) pattern changes from a 1 by 1 to a 2 by 2 structure on removal of the hydrogen. The interesting feature is that these changes can also be observed in the static-friction coefficient (fig. 18). The coefficient of static friction with a metal ball is low before the conversion occurs (fig. 18). Following conversion, the friction coefficient increases; therefore, changes in electronic state and structure of the surface are detected in the friction coefficient. Readsorbing the hydrogen returns the friction coefficient to its original lower value. These results correlate well with the additional features occurring in the energy-loss spectrum, such as core-level valence band excitations. Desorption experiments of hydrogen give binding energies that were comparable to removal of hydrogen from methane. As further evidence, XPS (X-Ray Photoelectron Spectroscopy) shows that the surface becomes conducting when the hydrogen is removed. The XPS carbon peak follows a bias voltage after the surface transformation, but does not prior to the transformation. We thus have a remarkable result. The surface is altered and these changes are detected in the macroscopic static-friction measurements. In conclusion, in spite of the great difficulties with which we are faced, I think there is experimental evidence that there are detectable surface effects in friction experiments. Both in the metal-metal and insulator-metal experiments, both reductions and increases in the static-friction coefficient are observed. There is still a great deal of carefully controlled experimental work which needs to be done in order to establish a sufficient data base for theorists, and the field is open for research of this nature.

OBSERVATIONS ON LUBRICATED CONTACTS

We now give some examples for more practical situations. Two contrasting studies of the effects of lubricant additives on wear were performed on a pin-on-disk apparatus by Ferrante and Brainard (refs. 24 and 25) and Ghose, Ferrante, and Honecy (ref. 26). The wear rates were determined from pin wear volume versus sliding distance curves (fig. 19). The first study by Ferrante and Brainard used zinc-dialkyl-dithiophosphates in di-butyl sebacate as a lubricant and found that the additive affects wear. In fact, thick reaction layers (~300 Å) are formed, as can be seen from depth profiles with Auger electron spectroscopy (ref. 24). The main active ingredients which were found on the surface were sulphur and the oxygen (fig. 20). The composition of these layers was ambient atmosphere dependent. In similar experiments by Ghose et al. with tri-cresyl-phosphate (TCP), no evidence of "thick" reaction layers (fig. 21) are found even though large variations in wear rate are observed as a function of lubricant composition (fig. 22). Again the wear rate behavior is ambient atmosphere dependent. This is possibly a case where surface effects,

such as adsorption of the TCP, dominate in a complicated system. Possibly the TCP molecules are somehow reducing the wear. An alternate explanation, however is that an easily sheared film is forming and it is removed during the wear process. This is an example where the wear protection mechanisms of two widely used anti-wear additives are not obvious. In this case, reactions of the additives with the surfaces are the dominant antiwear mechanisms. In figure 23 we show the results of wear studies with and without ZDP in different lubricant base stocks. Note that wear rate is base lubricant dependent. The oxalate gives higher wear presumably due to corrosion. The sebacate gives different behavior in dry air and dry nitrogen. The real world is exceedingly complicated.

ADHESION THEORY

Finally, we will report some results on the theory of metallic adhesion. In spite of the seeming importance of this field, there is still only the work of Ferrante and Smith (ref. 1) to refer to. We define adhesion, from the theoretician's standpoint, as the energy per unit area needed to cause brittle fracture between two pieces of metal along a plane as a function of separation. The force for separation is obtained from the derivative of the binding energy curve (fig. 24), and the maximum force for brittle fracture occurs at the inflection point of the binding energy curve.

Ferrante and Smith determined the strength and range of the force between the same and different metals. These results and the direction of metal transfer are important experimentally. They found that there is strong bonding between different metals in contact, that the range is of the order of an interplanar spacing, and that transfer occurs from the cohesively stronger to the cohesively weaker (table III). The limitation of these calculations is that the jellium model was used and that three-dimensional effects were included, using perturbation theory, and thus were only applicable to the densest packed planes of simple metals. Also, they give ideal strengths whereas the strength of real materials is dominated by defects and is thus substantially weaker than predicted by the model. An interesting feature of these binding energy curves is that they scale; i.e., they all have the same shape (fig. 25). In fact, Rose, Smith, and Ferrante (ref. 27) have shown that adhesion, cohesion, chemisorption, and diatomics have the same shape as long as no net charge transfer (e.g., ionic solids) has occurred in the bond (fig. 26). The implications of these results are explored in a series of papers (ref. 28).

Some remarks should be made regarding the nature of friction. In describing adhesion we have included only the force necessary to separate the surfaces in a normal direction; whereas friction refers to a tangential motion. Also, with friction we must consider loss mechanisms. In addition to a possible adhesive component (tensile adhesion on the sides of asperities) there are thermal, defect formation, and shear losses involved in friction. All of these contributions can be altered by surface preparation, adsorption, lubricants, and film formation from lubricant additives. To our knowledge there has been no theoretical modeling of the friction force comparable to the adhesion calculations. Similarly there has been no comparable theoretical modeling of the wear process, which involves similar effects. It is possible that, with recent advances in theory, some progress can be made with these problems.

CONCLUSION

In conclusion a great deal more effort is needed to put tribological research on a firmer scientific foundation. The field is multidisciplinary and is most properly a team effort of material scientists, chemists, mechanical engineers, and physicists. It ranges from the practical to the theoretical. The problems faced in tribology are extremely complex and are a combination of material properties, the nature of defects in solids, chemical reactions, interatomic and quantum mechanical forces, and fluid flow. There is a need for understanding each aspect of the problem (research such as the pioneering work of Bowden and Tabor (refs. 2 and 13-14), Tabor (ref. 17), and Buckley (ref. 18)) with the hope that a synthesis can be performed which generates an overall understanding. There is a need to establish a data base from which theoretical understanding can be generated.

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TABLE I. - METALLIC TRANSFER FOR DISSIMILAR METALS IN SLIDING CONTACT (refs. 14 and 15)

Disk	Rider	Transfer of metal from rider to disk
Tungsten	Iron	Yes
	Nickel	Yes
	Cobalt	Yes
Tantalum	Iron	No
	Nickel	No
	Cobalt	Yes
Molybdenum	Iron	No
	Nickel	No
	Cobalt	Yes
Niobium	Iron	No
	Nickel	No
	Cobalt	Yes

TABLE II. - FRICTION COEFFICIENT AND CONDITION OF WEAR TRACK FOR DISSIMILAR METALS IN SLIDING CONTACT (refs. 14 and 15)
[Sliding velocity, 33 cm/min; load, 500 g.]

Disk	Rider					
	Iron		Nickel		Cobalt	
	Friction coefficient, μ m	Condition of wear track	Friction coefficient, μ m	Condition of wear track	Friction coefficient, μ m	Condition of wear track
Tungsten	0.6	Plowed lightly	0.5	Plowed lightly	0.7 ↓	Smooth ↓
Tantalum	>1	Plowed	>1	Plowed		
Molybdenum	>1	Plowed	>1	Plowed		
Niobium	>1	Plowed	>1	Plowed		

TABLE III. - BINDING ENERGY COMPARISON
[All energy values taken from the minimum in the adhesive energy plots (fig. 22).]

Metal combination	Binding energy	
	Random registry	Perfect registry
Al(111)-Al(111)	490	715
Zn(0001)-Zn(0001)	505	545
Mg(001)-Mg(0001)	460	550
Na(110)-Na(110)	195	230
Al(111)-Zn(0001)	520	---
Al(111)-Mg(0001)	505	---
Al(111)-Na(110)	345	---
Zn(0001)-Mg(0001)	490	---
Zn(0001)-Na(110)	325	---
Mg(0001)-Na(110)	310	---

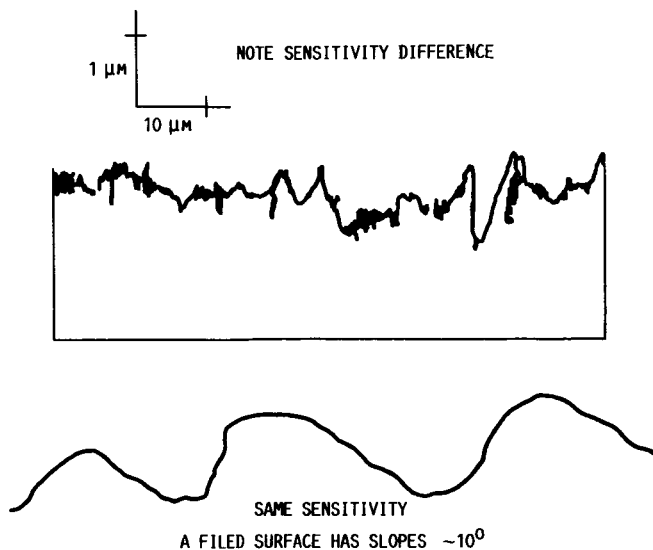


FIGURE 1. - A MAGNIFIED TAPERED SECTION OF A POLISHED STEEL SURFACE. EVEN RELATIVELY SMOOTH SURFACES HAVE MICROSCOPIC IRREGULARITIES. (FROM REF. 2.)

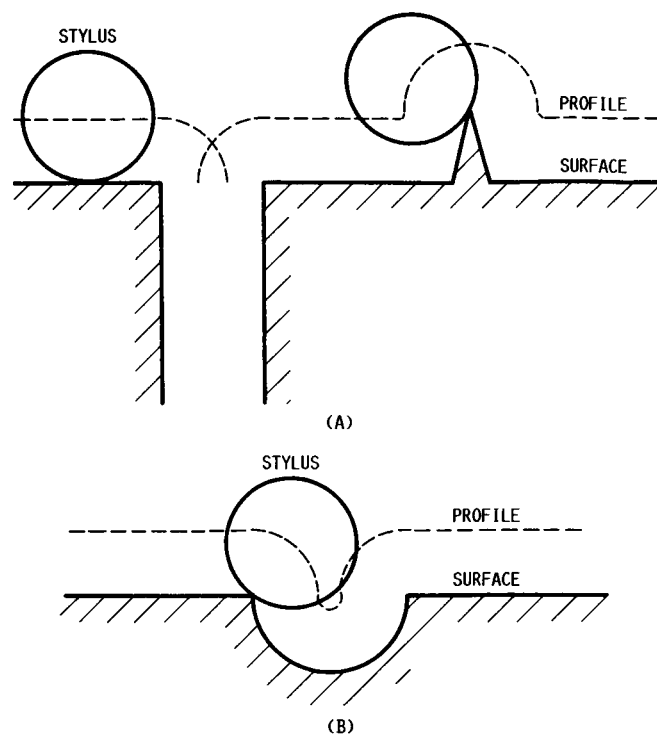


FIGURE 2. - ERROR DUE TO STYLUS RADIUS WITH SHARP PEAKS AND DEEP VALLEYS.

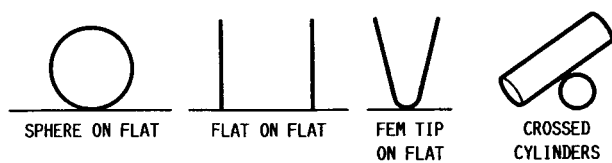
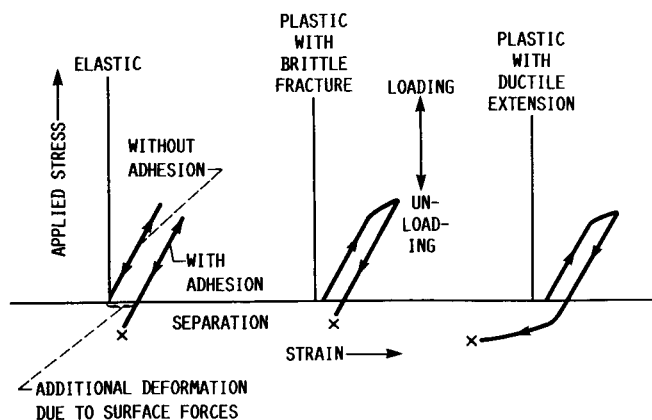
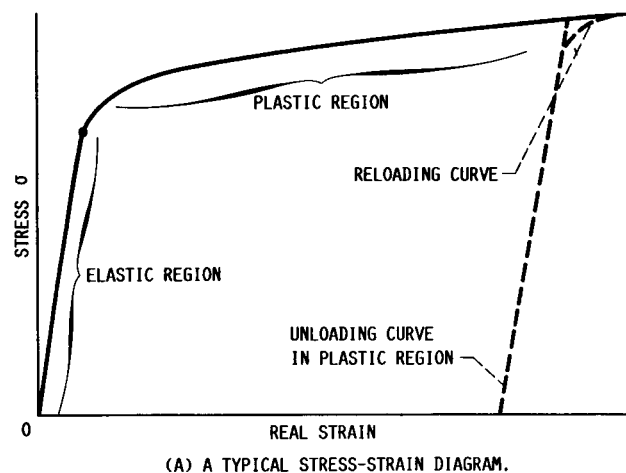


FIGURE 3. - SOME EXPERIMENTAL CONFIGURATIONS USED IN ADHESION EXPERIMENTS.

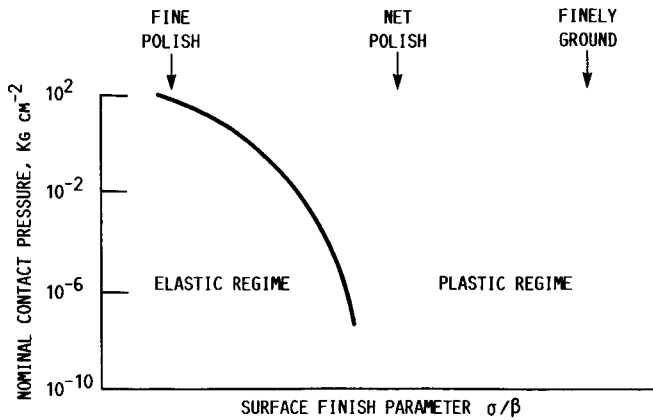


(B) LOADING AND UNLOADING STRESS-STRAIN CURVES WITH ADHESION (IDEALIZED SINGLE CONTACT).

FIGURE 4. - STRESS-STRAIN DIAGRAM FOR A TENSILE TEST.

ELASTIC-PLASTIC CRITERION

$$\psi = \frac{E}{R} \left(\frac{\sigma}{\beta} \right)^{1/2} \begin{cases} \psi < 0.6 \text{ ELASTIC} \\ \psi > 1.0 \text{ PLASTIC} \end{cases}$$



PLASTIC $A = \frac{W}{P_0}$

ELASTIC (MULTI-ASPRITY) $A = \frac{W}{P} (P = 0.1 \text{ TO } 0.3 P)$

ψ = PARAMETER OF MERIT
 W = LOAD
 σ = MEAN DEVIATION FOR GAUSSIAN
 β = ASPRITY TIP RADIUS
 E_0 = YOUNG'S MODULUS
 P_0 = PLASTIC YIELD PRESSURE

FIGURE 5. - THE ELASTIC-PLASTIC CRITERION OF SURFACE ASPERITIES. (FROM REFS. 13 AND 14.)

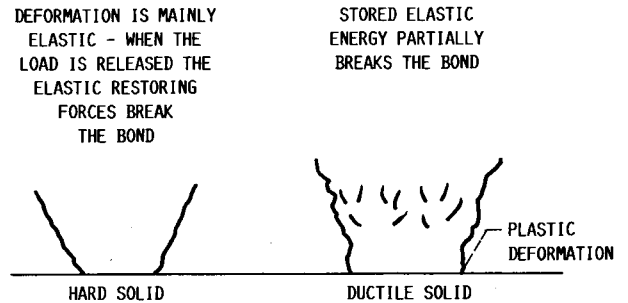


FIGURE 6. - EXAMPLES OF THE DIFFERENCES IN DEFORMATIONS ON LOADING AND UNLOADING OF HARD AND DUCTILE SOLIDS.

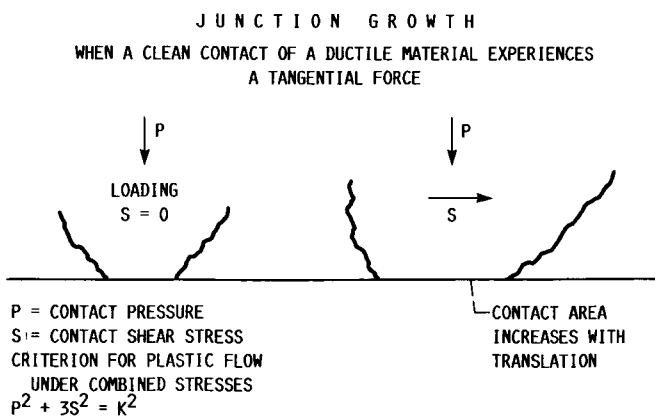


FIGURE 7. - EXAMPLE OF JUNCTION GROWTH WITH A DUCTILE SOLID WHERE TANGENTIAL FORCES AND VIBRATIONS CAN GREATLY AFFECT THE RESULTS OF ADHESION EXPERIMENTS.

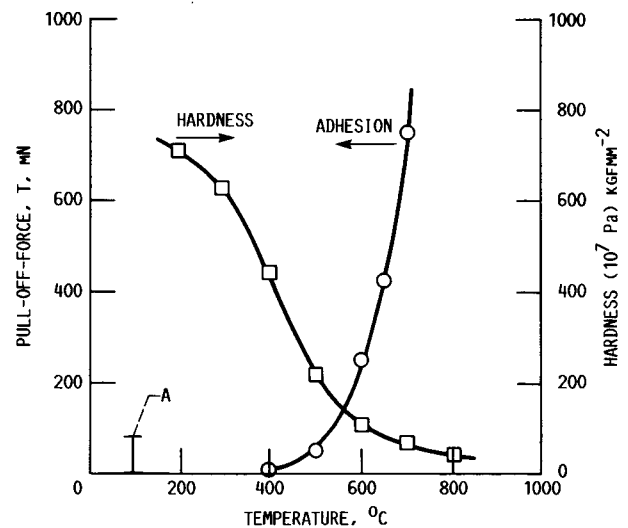


FIGURE 8. - VARIATION OF THE ADHESIVE STRENGTH (○) OF GERMANIUM WITH TEMPERATURE. THE COMPRESSION LOAD USED WAS 5 MN. THE LOW VALUES OF ADHESION INDICATED BY A AT THE BOTTOM LEFT-HAND CORNER OF THE FIGURE WERE OBTAINED ON ADHESIVE JUNCTIONS MADE AT 700 °C. THE VARIATION OF THE HARDNESS OF GERMANIUM WITH TEMPERATURE (□) IS INCLUDED FOR COMPARISON. (FROM REF. 4.)

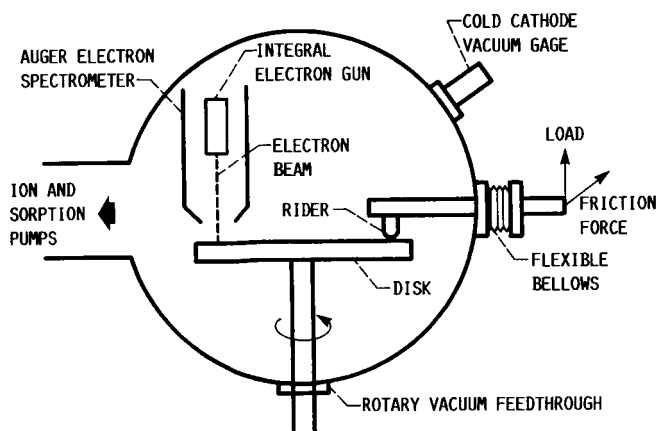


FIGURE 9. - EXPERIMENTAL FRICTION AND WEAR APPARATUS WITH AUGER ELECTRON SPECTROMETER.

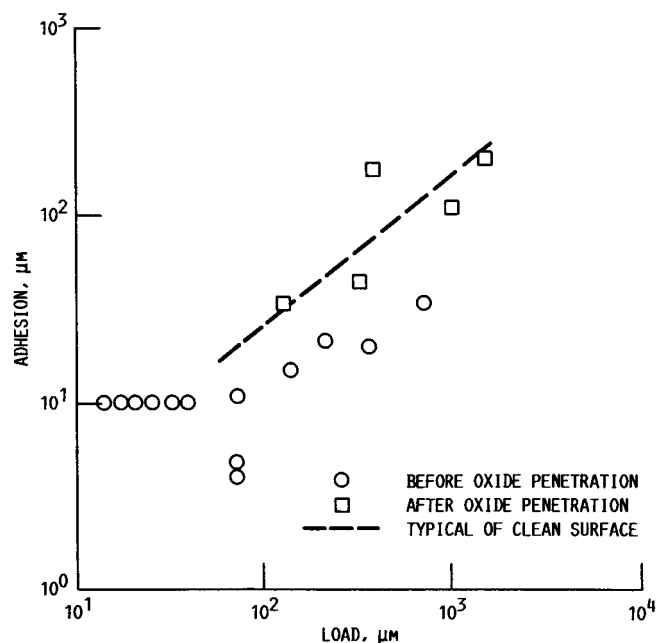


FIGURE 10. - ADHESION VERSUS LOAD WITH AN OXIDE FILM PRESENT FOR A TUNGSTEN FIELD EMISSION TIP ON A CLEAN AND OXIDIZED NICKEL. (FROM REF. 9.)

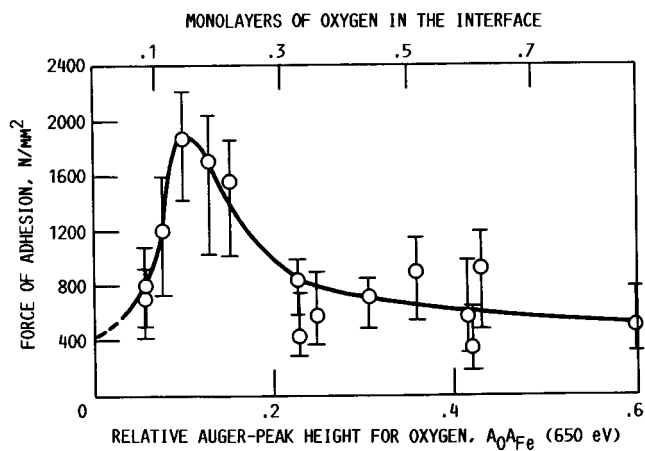
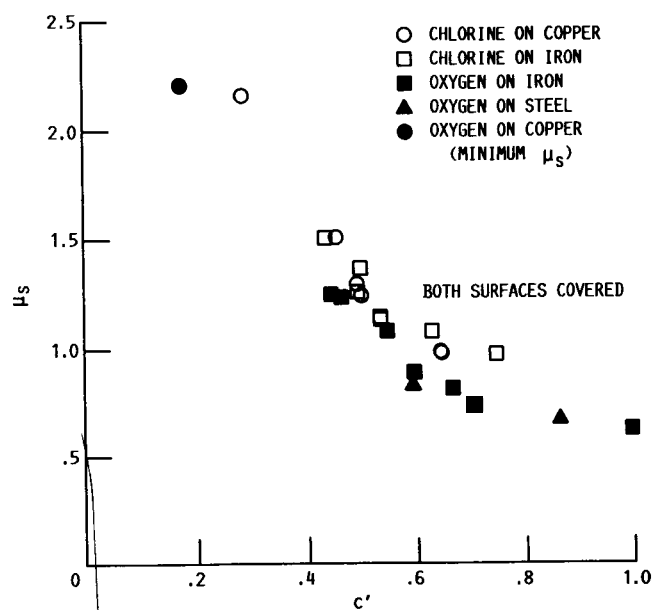
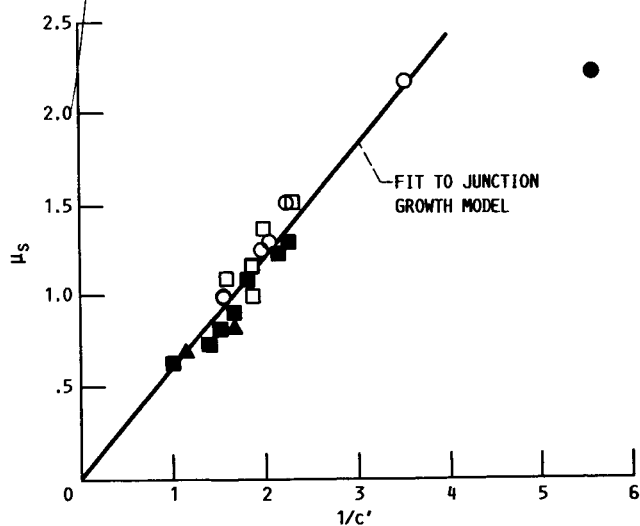


FIGURE 11. - FORCE OF ADHESION FOR VARIED OXYGEN COVERAGE IN THE INTERFACE BETWEEN THE TWO IRON SAMPLES. (FROM REF. 19.)

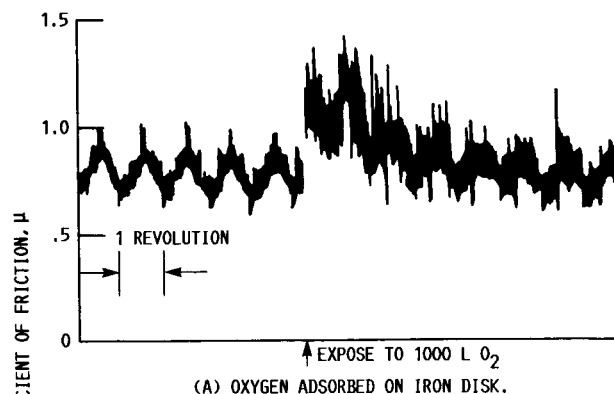


(A) STATIC COEFFICIENT OF FRICTION μ_s AS A FUNCTION OF ADSORBATE CONCENTRATION, c' .

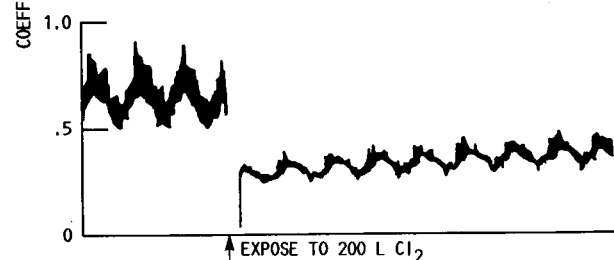


(B) STATIC COEFFICIENT OF FRICTION μ_s AS A FUNCTION OF INVERSE OF ADSORBATE CONCENTRATION.

FIGURE 12. - THE EFFECTS OF OXYGEN AND CHLORINE ADSORPTION ON STATIC FRICTION FOR A METAL-METAL CONTACT. (FROM REF. 20.)



(A) OXYGEN ADSORBED ON IRON DISK.



(B) CHLORINE ADSORBED ON IRON DISK.

FIGURE 13. - EFFECT OF OXYGEN AND CHLORINE ON THE FRICTION OF Fe SLIDING ON SAPPHIRE. (FROM REF. 21.)

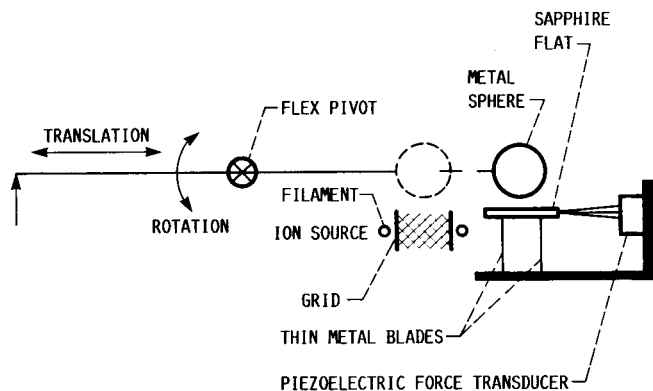


FIGURE 14. - FRICTION APPARATUS IN ULTRAHIGH VACUUM.

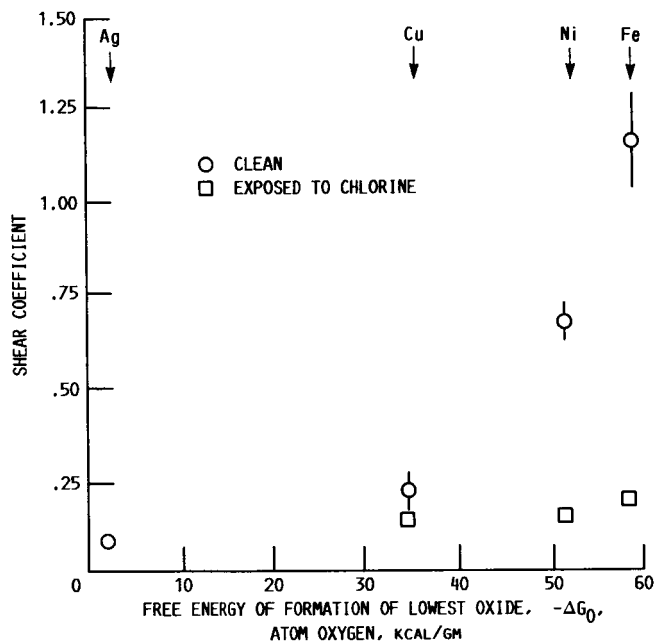


FIGURE 15. - SHEAR COEFFICIENTS OF CLEAN AND CHLORINATED METALS IN CONTACT WITH CLEAN (0001) SAPPHIRE PLOTTED VERSUS FREE ENERGY OF OXIDE FORMATION OF THE LOWEST METAL OXIDE. THE MEAN DEVIATION IS INDICATED BY THE VERTICAL BARS. (FROM REF. 22.)

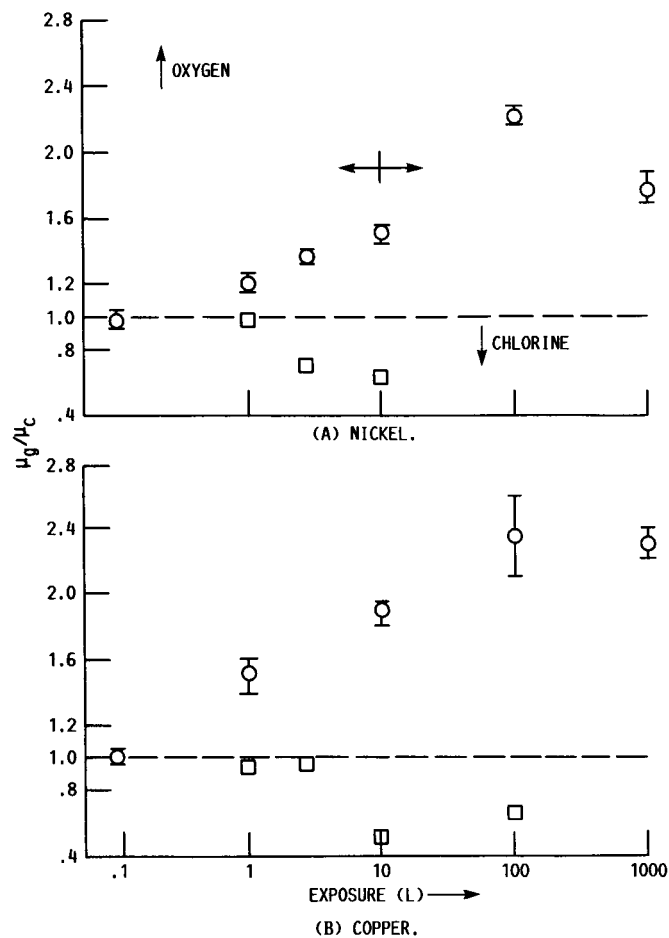
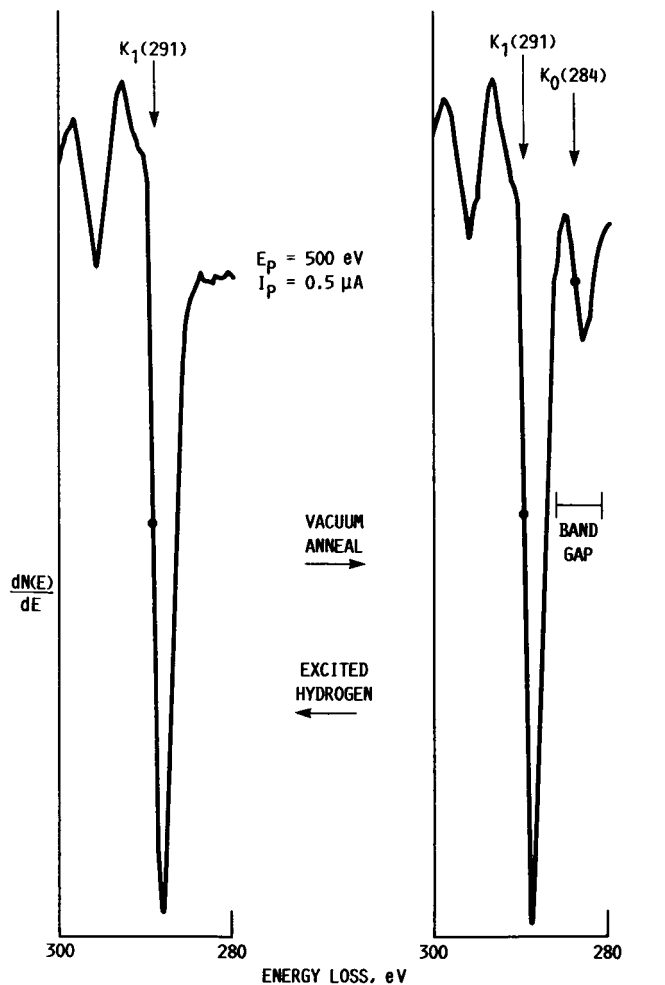


FIGURE 16. - RATIO OF STATIC FRICTION COEFFICIENT AFTER EXPOSURE TO GAS μ_g TO STATIC FRICTION COEFFICIENT OF CLEAN CONTACT μ_c PLOTTED AGAINST EXPOSURE TO OXYGEN (○) AND CHLORINE (□). THE SOLID POINTS ARE SIMPLE AVERAGES AND THE ERROR BARS INDICATE THE HIGHEST AND LOWEST VALUES OBTAINED FOR A NUMBER OF EXPERIMENTAL TRIALS AT THE SAME EXPOSURE. VALUE OF $\mu_g/\mu_c > 1$ INDICATE A STRONGER CONTACT AND VALUES < 1 INDICATE A WEAKER CONTACT FOLLOWING EXPOSURE TO THE GAS. (FROM REF. 22.)



(A) SURFACE IS EITHER FRESHLY POLISHED OR EXPOSED TO EXCITED HYDROGEN.

(B) DIAMOND HAS BEEN ANNEALED AT $\sim 900^\circ\text{C}$ TO DEVELOP K_0 TO ITS MAXIMUM SIZE OF $0.14 K_1$.

FIGURE 17. - IONIZATION LOSS SPECTRA OF DIAMOND (110). THE VALUES OF THE ENERGY LOSS DEPICTED ARE TAKEN AT THE ARITHMETIC MEAN OF THE MAXIMUM AND MINIMUM IN THESE DERIVATIVE SPECTRA. (FROM REF. 23.)

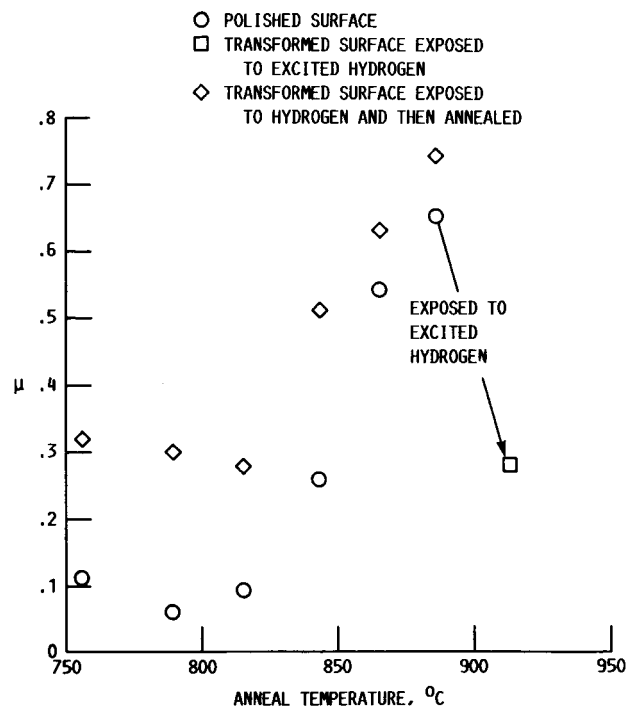


FIGURE 18. - COPPER-DIAMOND STATIC FRICTION COEFFICIENT AS A FUNCTION OF DIAMOND ANNEALING TEMPERATURE. (FROM REF. 23.)

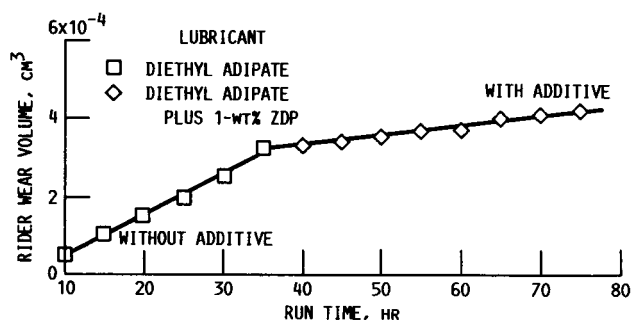


FIGURE 19. - WEAR VOLUME AS FUNCTION OF TIME FOR PURE IRON SLIDING ON M-2 TOOL STEEL. SLIDING VELOCITY, 2.5 cm/sec ; LOAD, 4.9 N ; ATMOSPHERE, DRY AIR; LUBRICANT, DIETHYL ADIPATE.

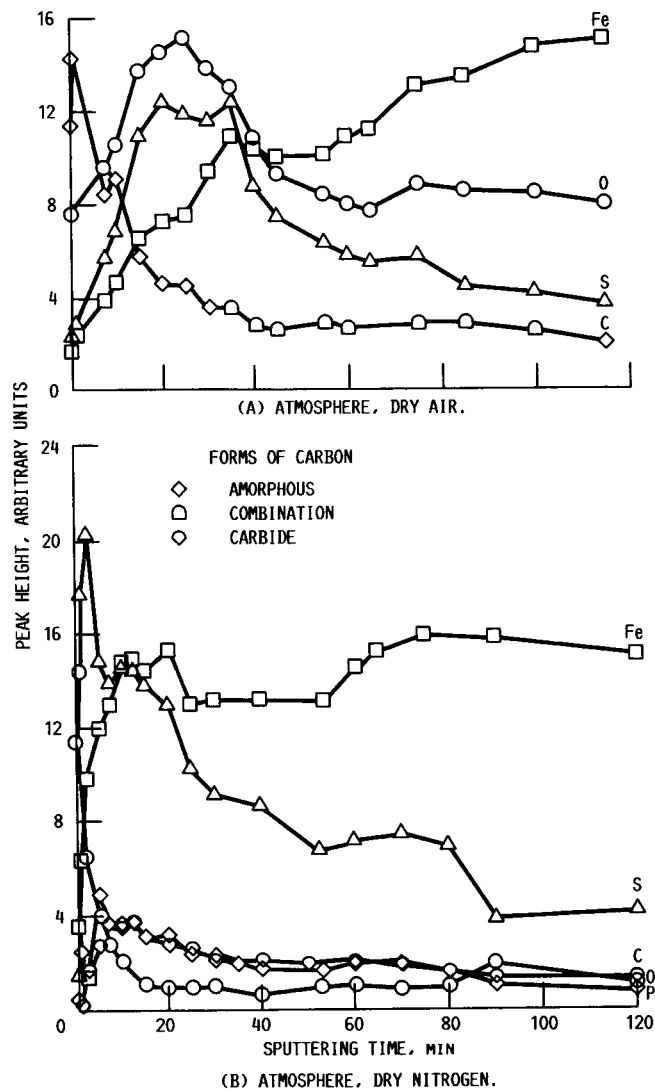


FIGURE 20. - ELEMENTAL DEPTH PROFILE OF A WEAR SCAR ON AN IRON PIN RUN IN DIBUTYL SEBACATE PLUS 1 PERCENT ZDP. SLIDING SPEED 2.5 CM/SEC. LOAD 4.9 N.

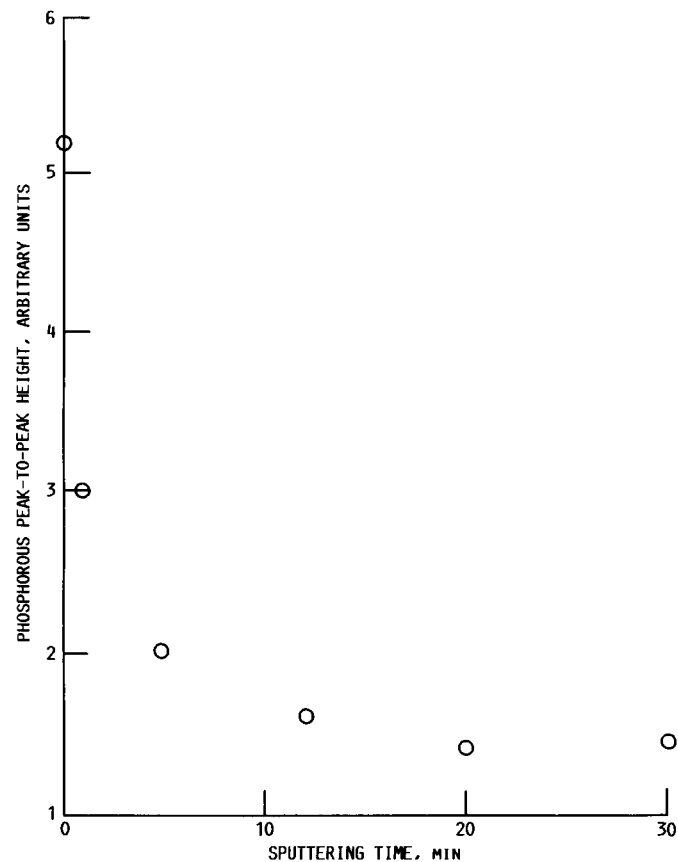
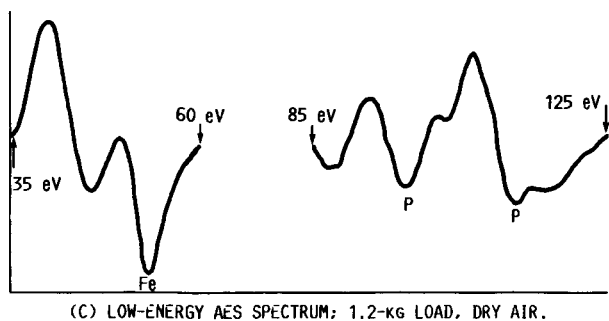
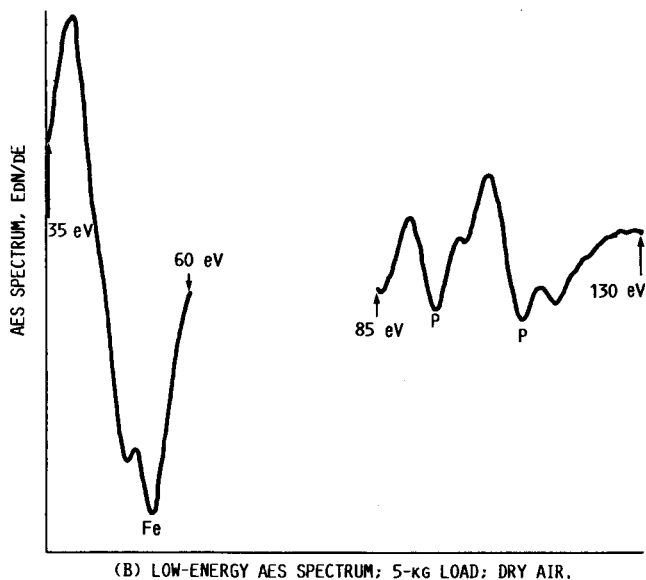
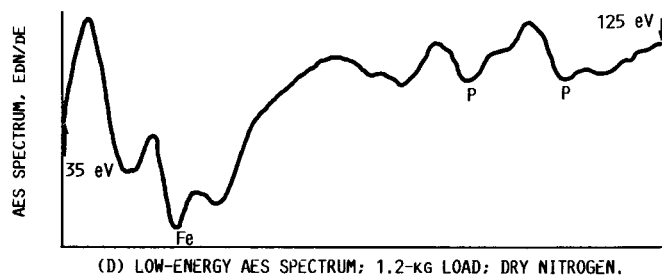
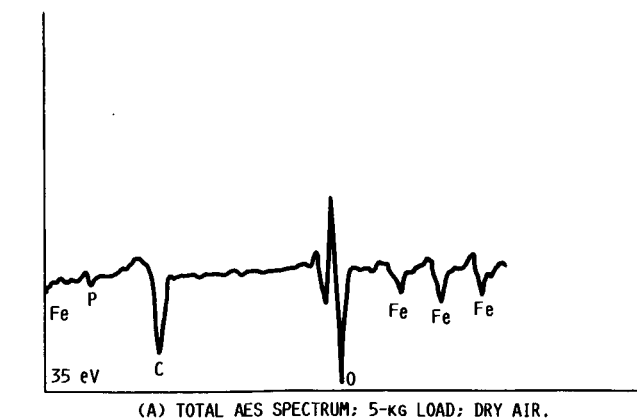


FIGURE 21. - TOTAL AND LOW-ENERGY AES SPECTRA OF LUBRICANT WITH TCP ADDITIVE UNDER TWO DIFFERENT LOADS IN TWO DIFFERENT ATMOSPHERES.

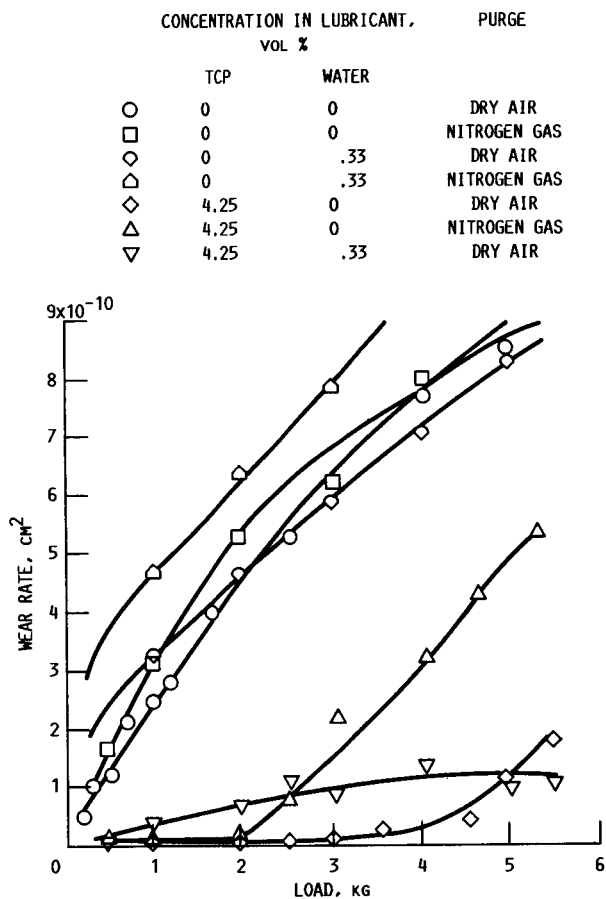


FIGURE 22. - WEAR RATE VERSUS LOAD FOR VARIOUS CONCENTRATIONS OF TRICRESYL PHOSPHATE (TCP) AND WATER IN LUBRICANT UNDER ATMOSPHERIC VARYING CONDITIONS.

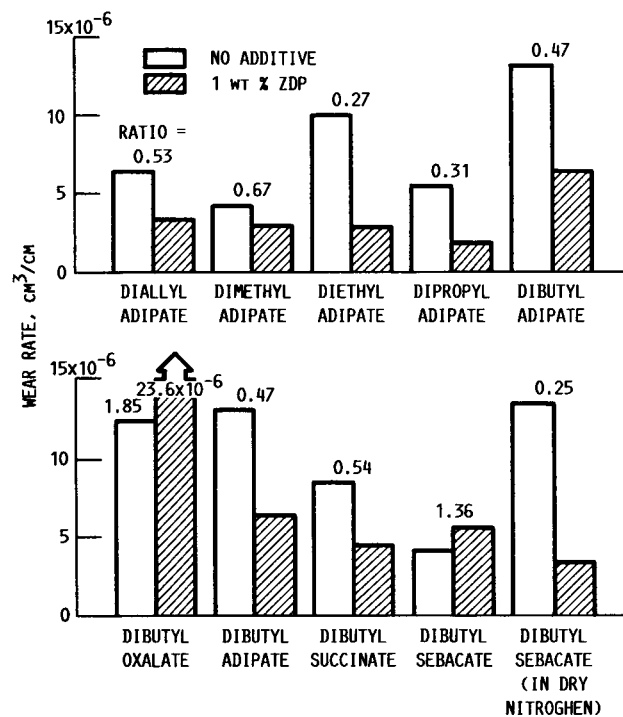


FIGURE 23. - WEAR RATES OF PURE IRON SLIDING ON M-2 TOOL STEEL IN VARIOUS DIESTERS WITH AND WITHOUT ZDP IN DRY AIR AND IN DRY NITROGEN FOR DIBUTYL SEBACATE. 2.5 CM/SEC SLIDING SPEED WITH A 4.0 N LOAD.

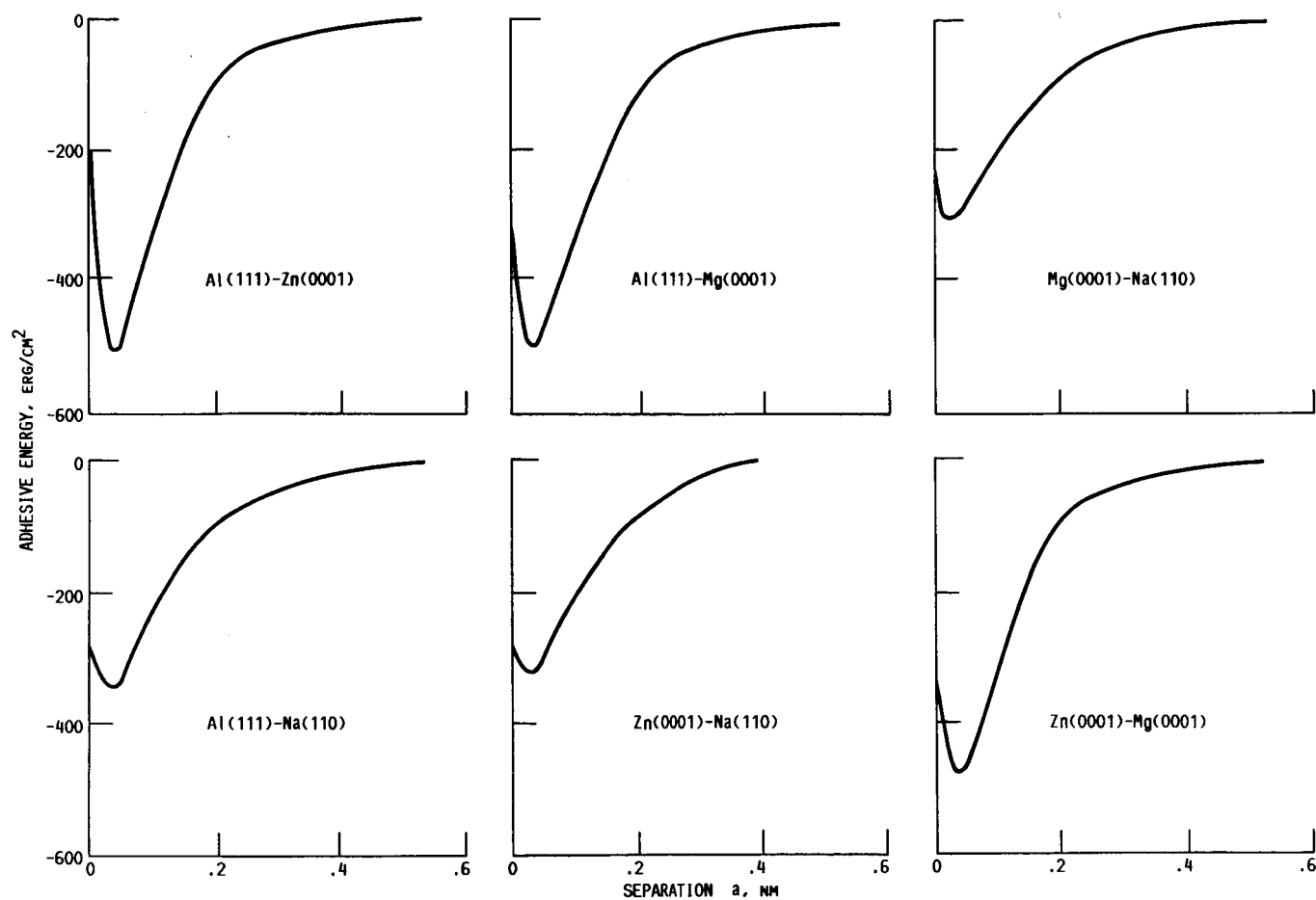


FIGURE 24. - ADHESIVE BINDING ENERGY VERSUS SEPARATION a . INCOMMENSURATE ADHESION IS ASSUMED.

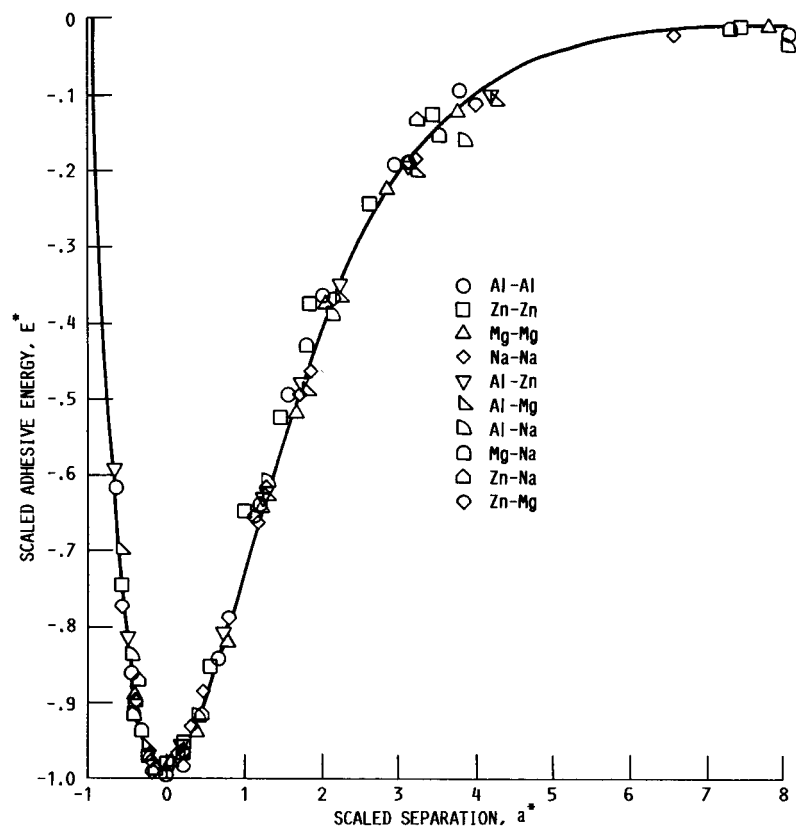


FIGURE 25. - SCALED ADHESIVE BINDING AS FUNCTION OF SCALED SEPARATION ENERGY.

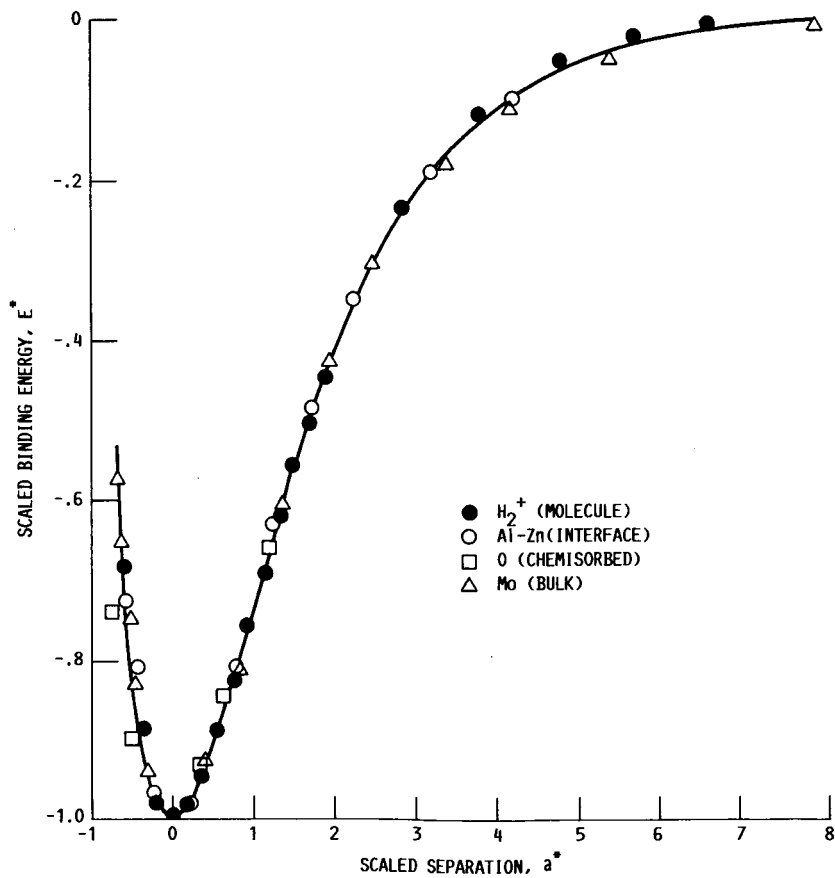


FIGURE 26. - BINDING ENERGY AS A FUNCTION OF INTERATOMIC SEPARATION FOR FOUR SYSTEMS AS NOTED.

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16. Abstract Tribology, the study of friction and wear of materials, has achieved a new interest because of the need for energy conservation. Fundamental understanding of this field is very complex and requires a knowledge of solid-state physics, material science, chemistry, and mechanical engineering. Initiating a research program in tribology requires an understanding of these complexities. The present paper is meant to be didactic in nature and outlines some of the considerations needed for such a program. The approach is to first present a simple model, a field emission tip in contact with a flat surface, in order to elucidate important considerations, such as contact area, mechanical deformations, and interfacial bonding. Then examples, from illustrative experiments are presented. Finally, the current status of physical theories concerning interfacial bonding are presented.					
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